

Quantum Gravity Gradiometer Development for Space

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Brief Outline

I. Introduction

II. Laboratory Instrument Development

- a) Hardware subsystems
- b) Performance characterization
- c) Initial measurement results

III. Mobile System Development

IV. Future Work and Conclusions



ABSTRACT: Gravity gradiometers based on atom-wave interferometry hold great promise for advanced gravity studies from space. The potential sensitivity of these instruments can provide high-resolution maps of mass distributions above and below the surface of planets, as well as temporal monitoring of dynamical processes affecting these mass distributions. Funded by NASA's Earth Science Technology Office, we are developing an atom interferometer-based gravity gradiometer in the laboratory as a prototype for a future space-flyable instrument.

Space-Based Gravity Studies

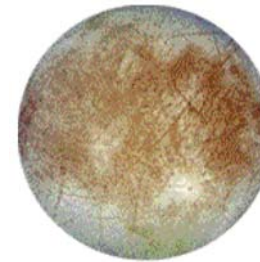
Earth and planetary structure

- Lithospheric thickness and composition
- Lateral mantle density heterogeneity
- Deep interior studies
- Translational oscillations between core and mantle

Earth and planetary climate effects

- Surface and ground water storage
- Ocean circulation
- Tidal variations
- Polar ice changes, glacial movements

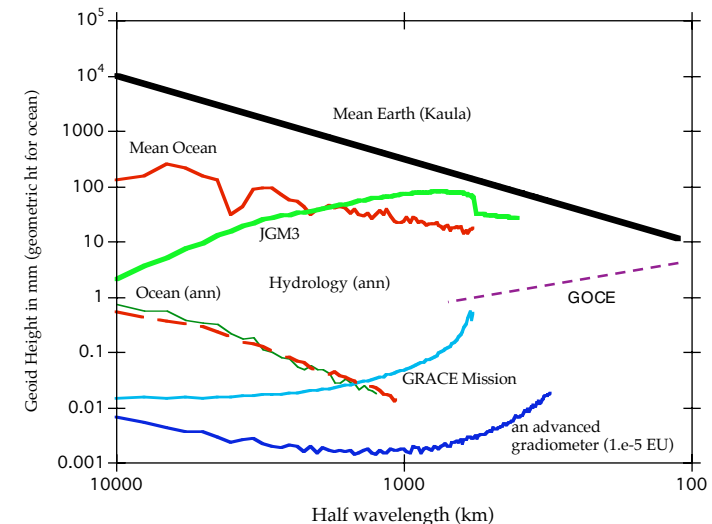
Beyond GRACE capability ...



*A hidden ocean beneath
Europa's surface?*

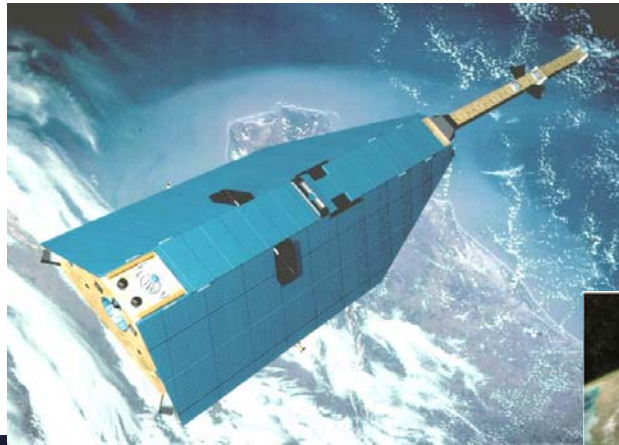


*3-D simulation of
compressible mantle
convection*

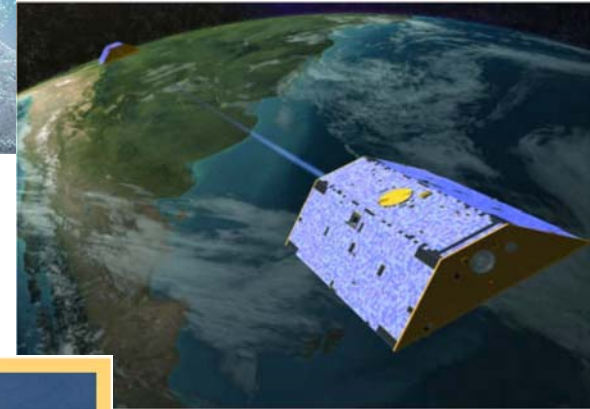


Advanced Gravity Missions

GPS-CHAMP high-low satellite-to-satellite and ground-based laser tracking



GRACE uses low-low satellite-to-satellite microwave tracking and ranging for long (~500 km) wavelength and time variation



GOCE uses 3-axis accelerometers for high resolution (100 km) gradiometry

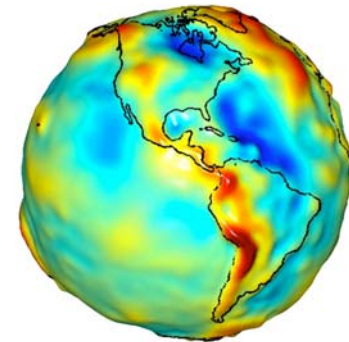


Quantum gravity gradiometer uses atoms as drag-free test masses for high spatial resolution and high stability for monitoring temporal variations

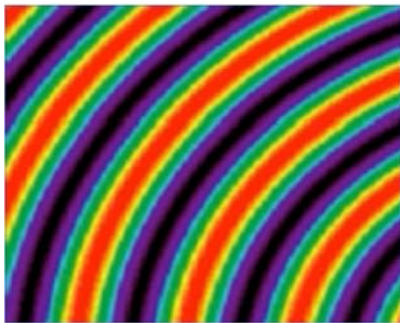


Gravity Recovery and Inversion Methods

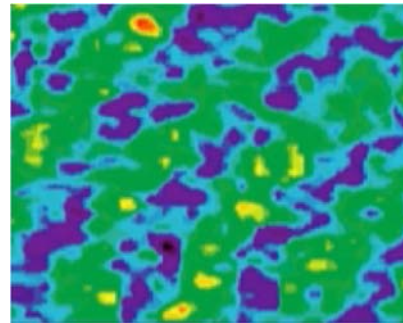
Gravity gradiometry measures the relative accelerations of two or more test masses to remotely “weigh” nearby distributions of mass. Inversion algorithms have been developed to recover the gravity fields and determine the underlying mass distributions.



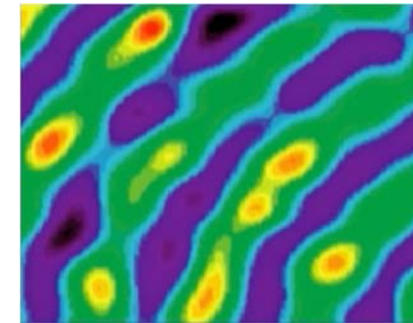
Geoid height over North America as measured by the GRACE satellites



A test model of mass variations due to horizontal pressure gradients on the ocean bottom



Simulated horizontal gravity gradient data as taken by a polar orbiter after one month at 200 km altitude.



Reconstruction of the source function by gravity gradient data inversion



Light-Pulse Atom Interferometry

Stimulated Raman transitions modify an atom's momentum by

$$\Delta \mathbf{p} = \hbar \mathbf{k}_{\text{eff}}$$

where $\mathbf{k}_{\text{eff}} \equiv \mathbf{k}_1 - \mathbf{k}_2 \approx 2\mathbf{k}_1$ for velocity-sensitive transitions.

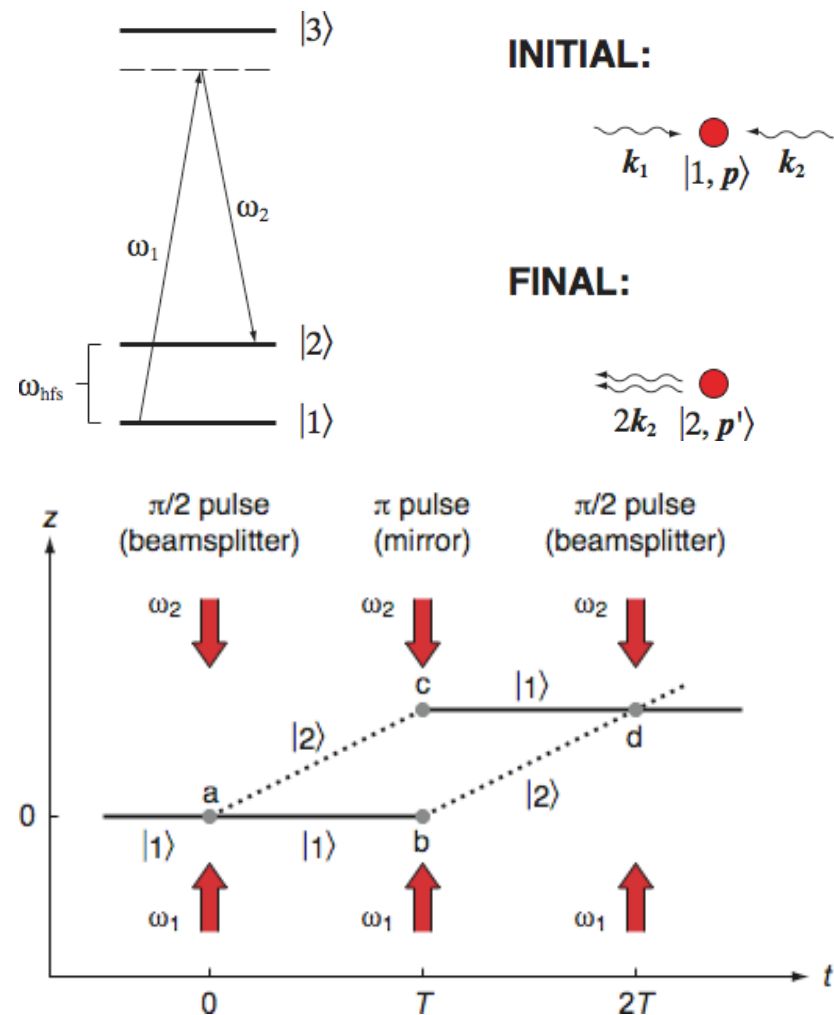
The atom interferometer is realized by a three-pulse ($\pi/2$ – π – $\pi/2$) Raman sequence.

The transition probability resulting from this sequence is given by

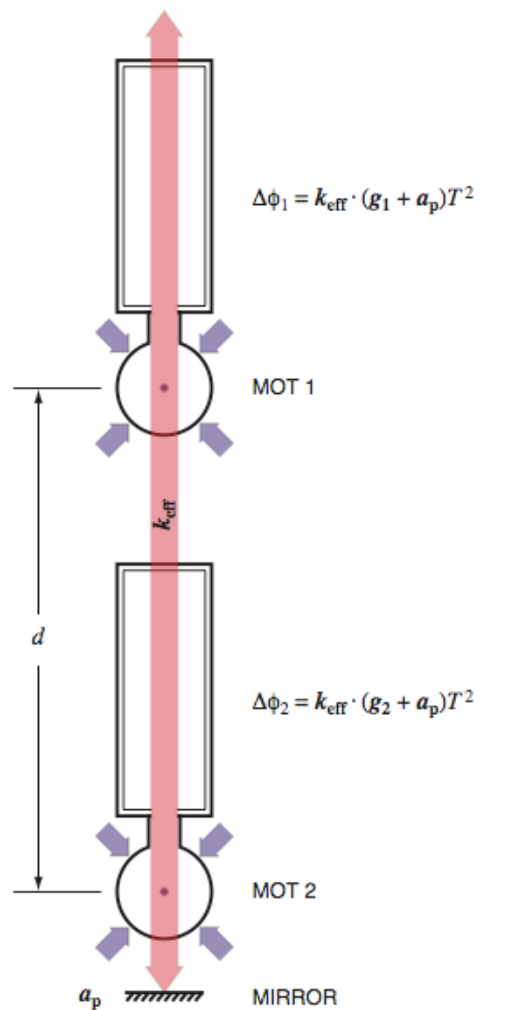
$$P = [1 - \cos(\Delta\phi)]/2$$

and the phase shift $\Delta\phi$ is related to the local acceleration \mathbf{a} by $\Delta\phi = \mathbf{k}_{\text{eff}} \cdot \mathbf{a} T^2$, where T is the time between pulses.

This phase shift is measured by monitoring the relative populations following this pulse sequence.



Gravity Gradiometry with Atom Interferometers



The phase shift is measured simultaneously in two atom interferometers using *common laser beams* to drive the Raman transitions.

The phase shift in each interferometer is given by

$$\Delta\phi_i = \mathbf{k}_{\text{eff}} \cdot (\mathbf{g}_i + \mathbf{a}_p) T^2$$

where \mathbf{a}_p is the acceleration of the mirror platform and \mathbf{g}_i is the average gravitational acceleration at the position of the i^{th} atom interferometer.

The linear gravity gradient is determined from the difference in the measured phase shifts in the two interferometers separated by a distance d :

$$\Delta g / \Delta z = (\Delta\phi_1 - \Delta\phi_2) / (k_{\text{eff}} T^2 d)$$

and common-mode platform vibrations \mathbf{a}_p are effectively cancelled.

\Rightarrow *Measurement possible on moving platforms ...*



Operation in Microgravity Environments

Advantages in microgravity

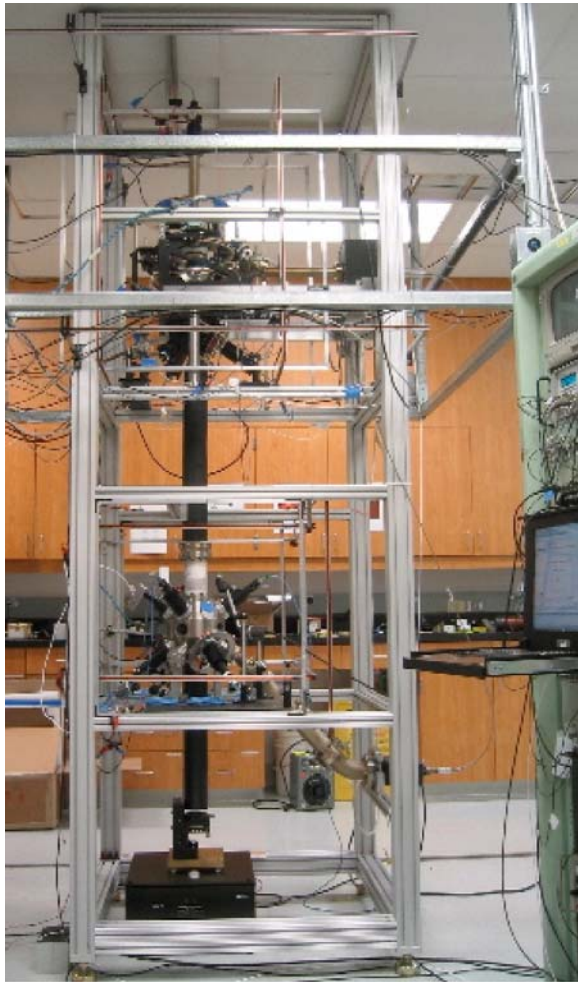
- Enhancement of measurement sensitivity due to longer interaction times
 - Sensitivity increases as T^2 , in contrast to Fourier transform-limited measurements in atomic clocks
 - Measurement of 3-D gravity fields feasible
- Absolute stability facilitates temporal monitoring and time-averaged measurements

Long baseline measurement issues

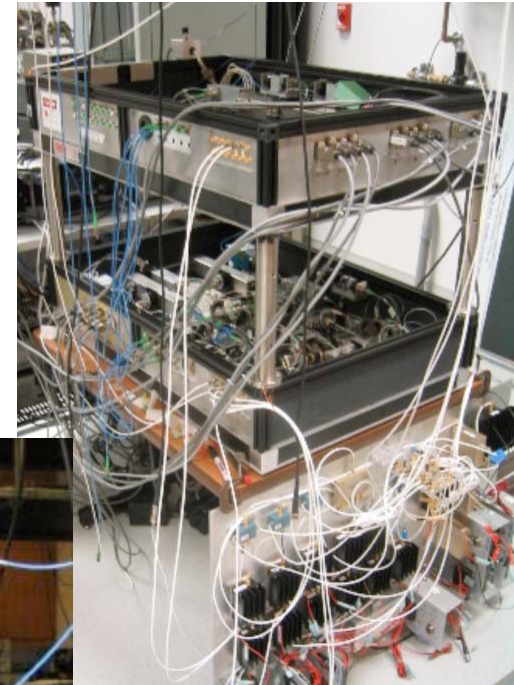
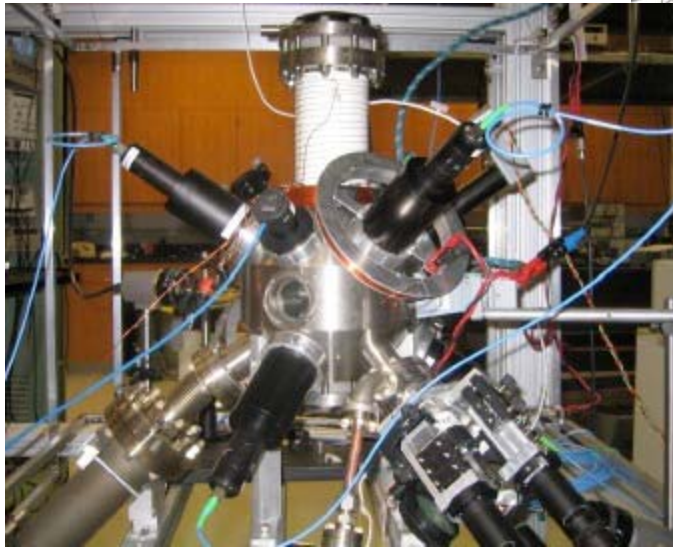
- Determination of measurement baseline from cold atom clouds' centroid positions
- Atom cloud size issues
 - Static gradient compensation
 - Raman beam size and transverse profile
- Rotational sensitivity
 - Alignment of measurement axis on orbiting platform
 - Coriolis forces
- Laser short-term stability
- Instrument dynamic range and vibration



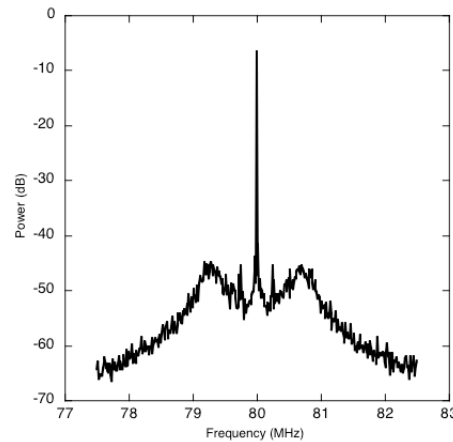
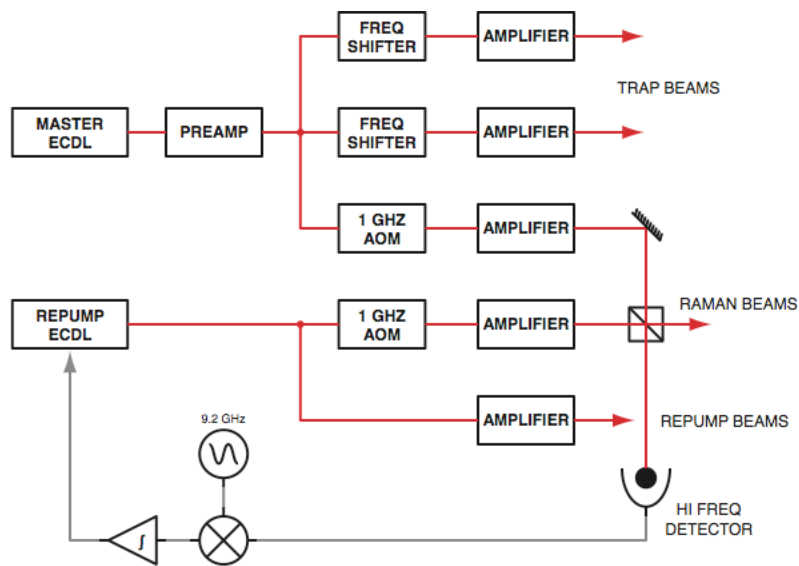
Phase I: Laboratory Instrument Development



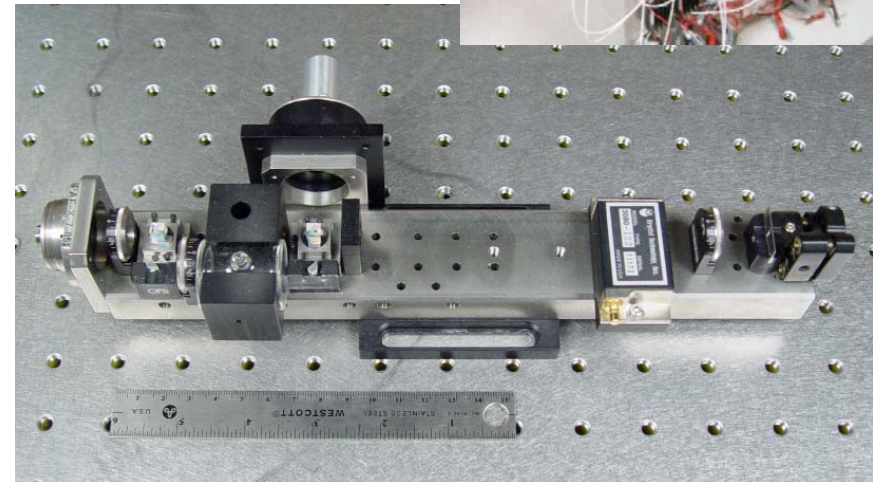
Dual atom interferometer-based **gravity gradiometer** in the laboratory (*left*), close-up of the **atomic physics package APP-2** (*below*), and modular **laser and optics system** (*right*).



Modular Laser and Optical System



Laser system schematic (*above, left*),
beatnote between Raman lasers (*above, middle*), complete assembled **laser and optics system** (*above, right*), and close-up of a saturated absorption **laser lock module** (*lower right*).

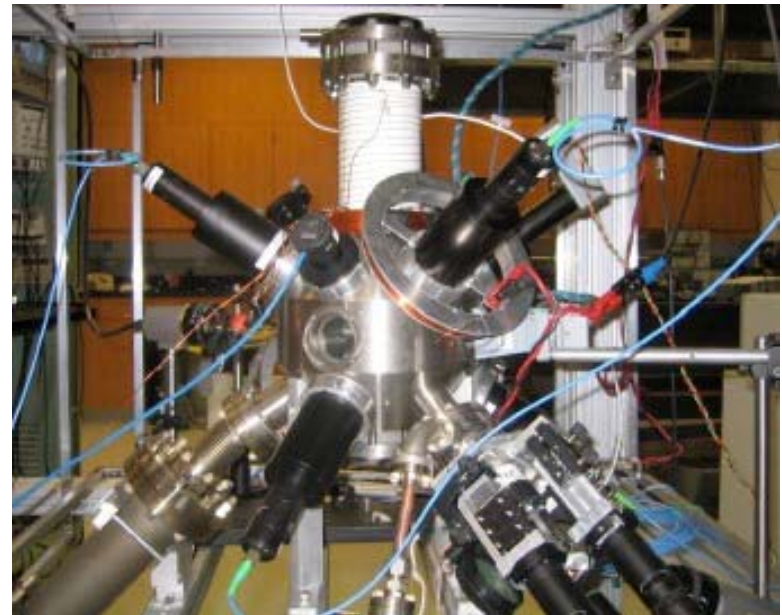


Atomic Physics Package

All the necessary manipulations of cesium atoms are performed with lasers and occur inside the two **atomic physics packages** (APPs).

Each measurement cycle includes:

1. Load up to 10^9 atoms into a UHV MOT from a separate cold atom beam source, then cool to 2 μK in an optical molasses.
2. Launch cold atoms vertically.
3. State- and velocity-select atoms to produce atoms in the magnetic field-insensitive spin states and with a narrow velocity profile.
4. Drive interferometer transitions using Raman laser pulses.
5. Measure interferometer transition probability using state-resolved laser-induced fluorescence detection.

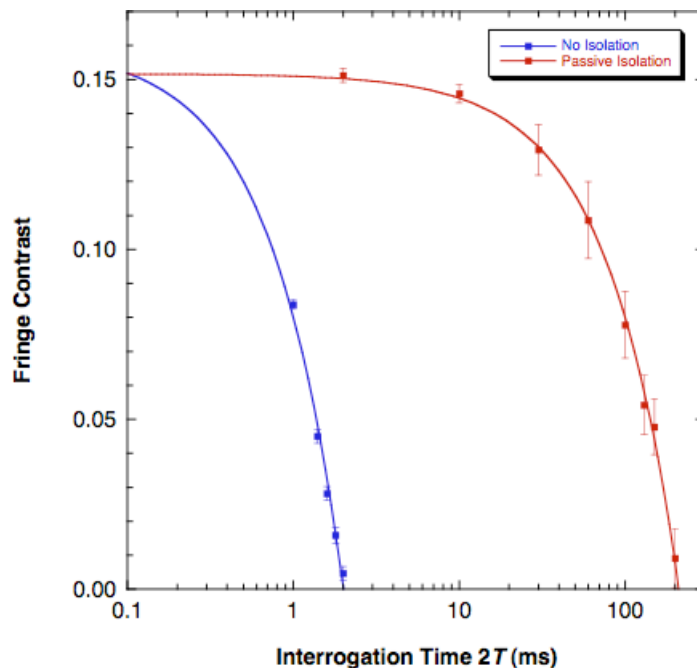


Above: The **atomic physics package** APP-2. The 2D-MOT cold atom beam source is visible in the lower right quadrant.



Vibration Isolation Platform

Commercial **passive vibration isolation platform** (right) for the Raman laser retro-optics. The entire platform with optics is housed inside an enclosure to minimize perturbations from acoustic noise and air currents.



Without vibration isolation, the fringe contrast is completely degraded for interrogation times longer than 2 ms due to environmental noise. Passive vibration isolation allows useful interrogation times up to 200 ms.

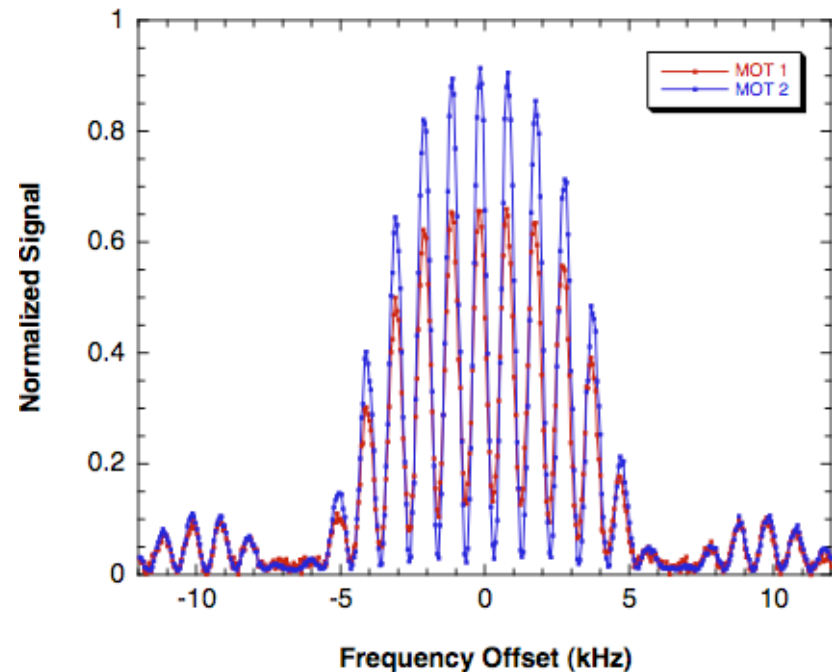
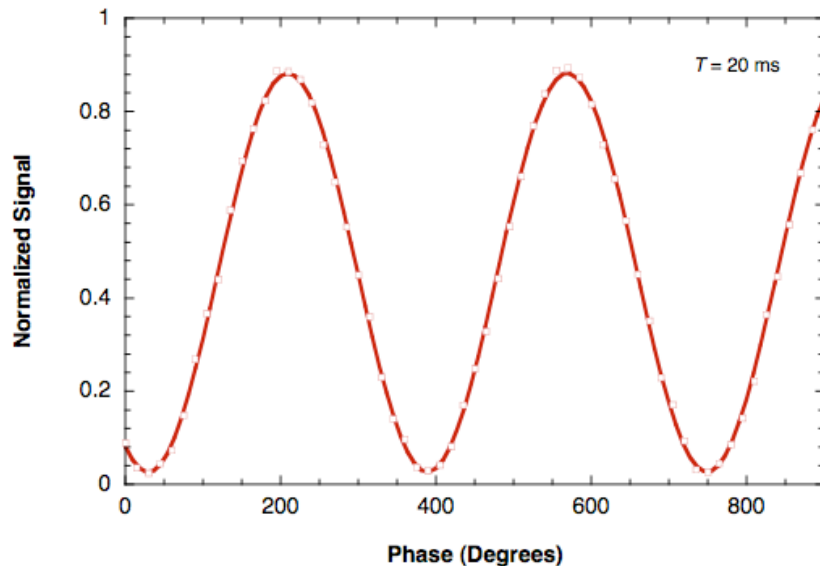
Even longer times possible with improved isolation or other phase compensation schemes ...



Characterization of Performance

Doppler-insensitive transitions are useful for characterizing the intrinsic contrast and signal-to-noise levels in the individual atom interferometers.

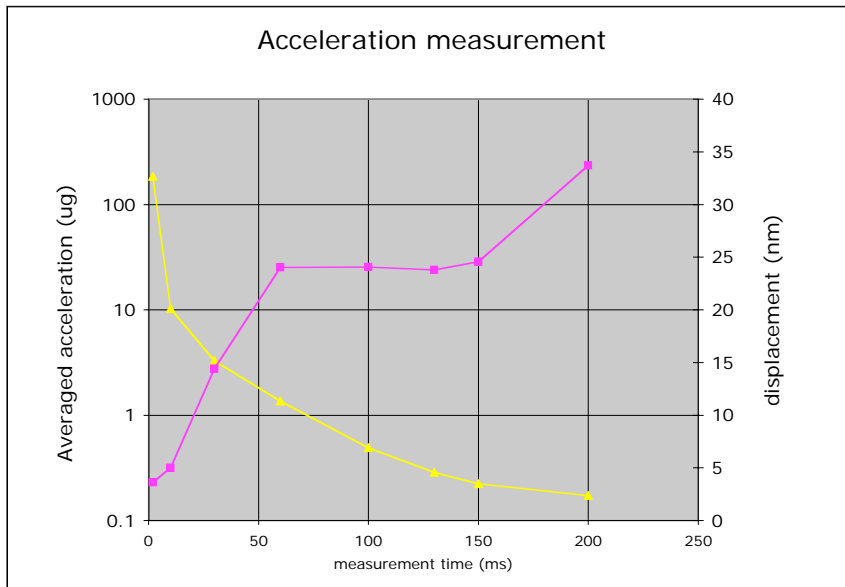
Right: **Ramsey interference spectra** observed in the dual interferometers using two Doppler-insensitive Raman $\pi/2$ pulses separated by 1 ms.



Left: **Ramsey interferometer fringes** obtained by scanning the phase of the second pulse relative to the first for an interrogation time of 20 ms. The fringe contrast is 86%, and the SNR is 185.



Gravimeter and Gradiometer Sensitivities



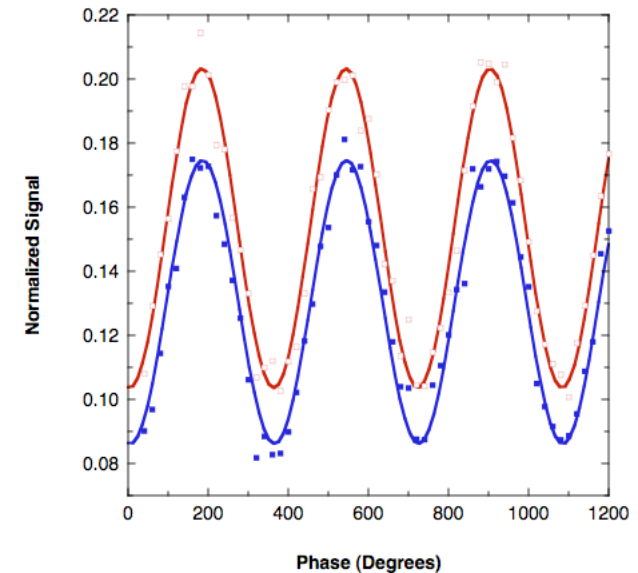
Gradiometer sensitivity

For the baseline separation of $d = 1.4$ m, we infer a gradiometer sensitivity of $34 \text{ E Hz}^{-1/2}$ at $T = 100$ ms ($5 \text{ E Hz}^{-1/2}$ with 10 m baseline) for our system.

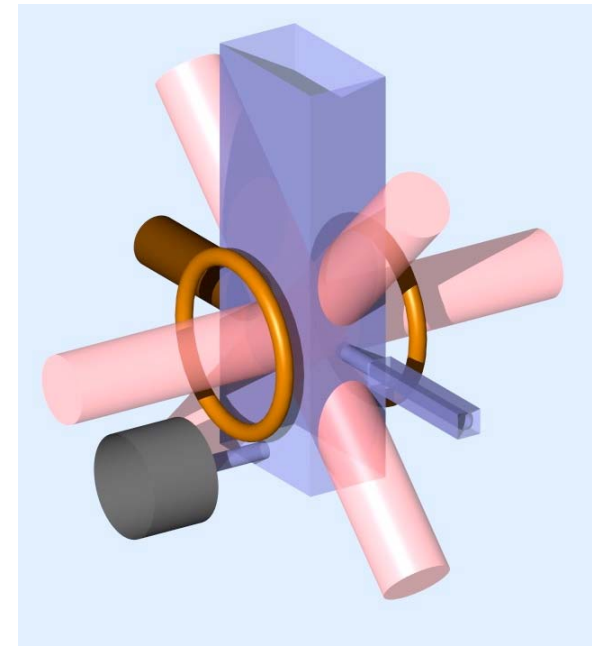
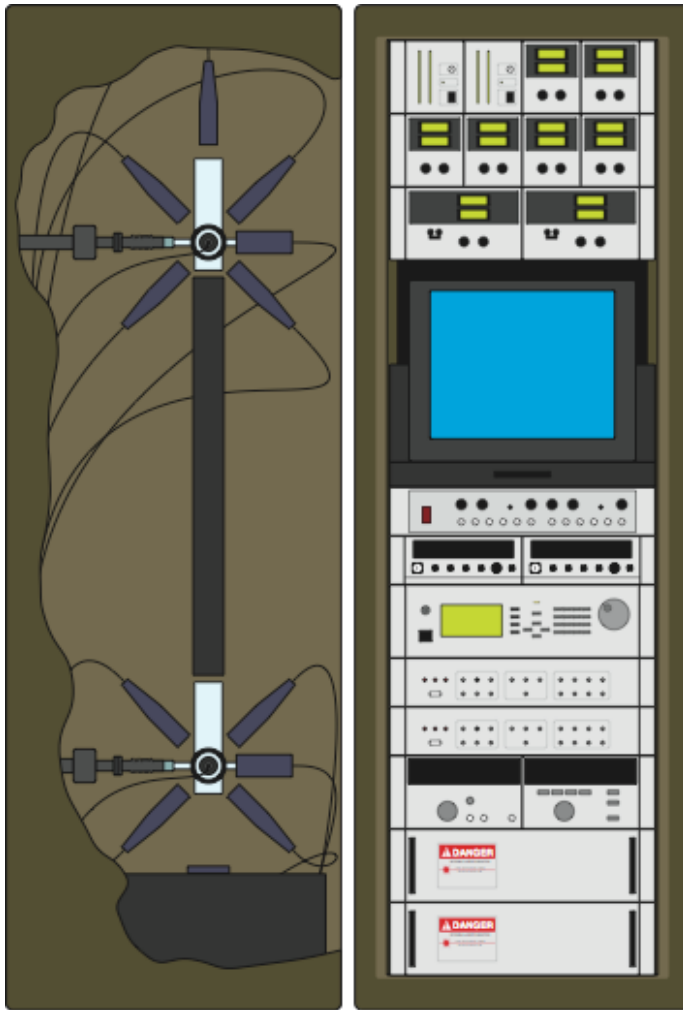
Accelerometer performance

Demonstrated atom interferometer fringes for interaction times up to $2T = 200$ ms, limited by environmental noise on passively-isolated reference platform.

Demonstrated an acceleration measurement sensitivity of $\sim 3 \times 10^{-9} \text{ g Hz}^{-1/2}$ in a single interferometer.



Phase II: Mobile Instrument Development

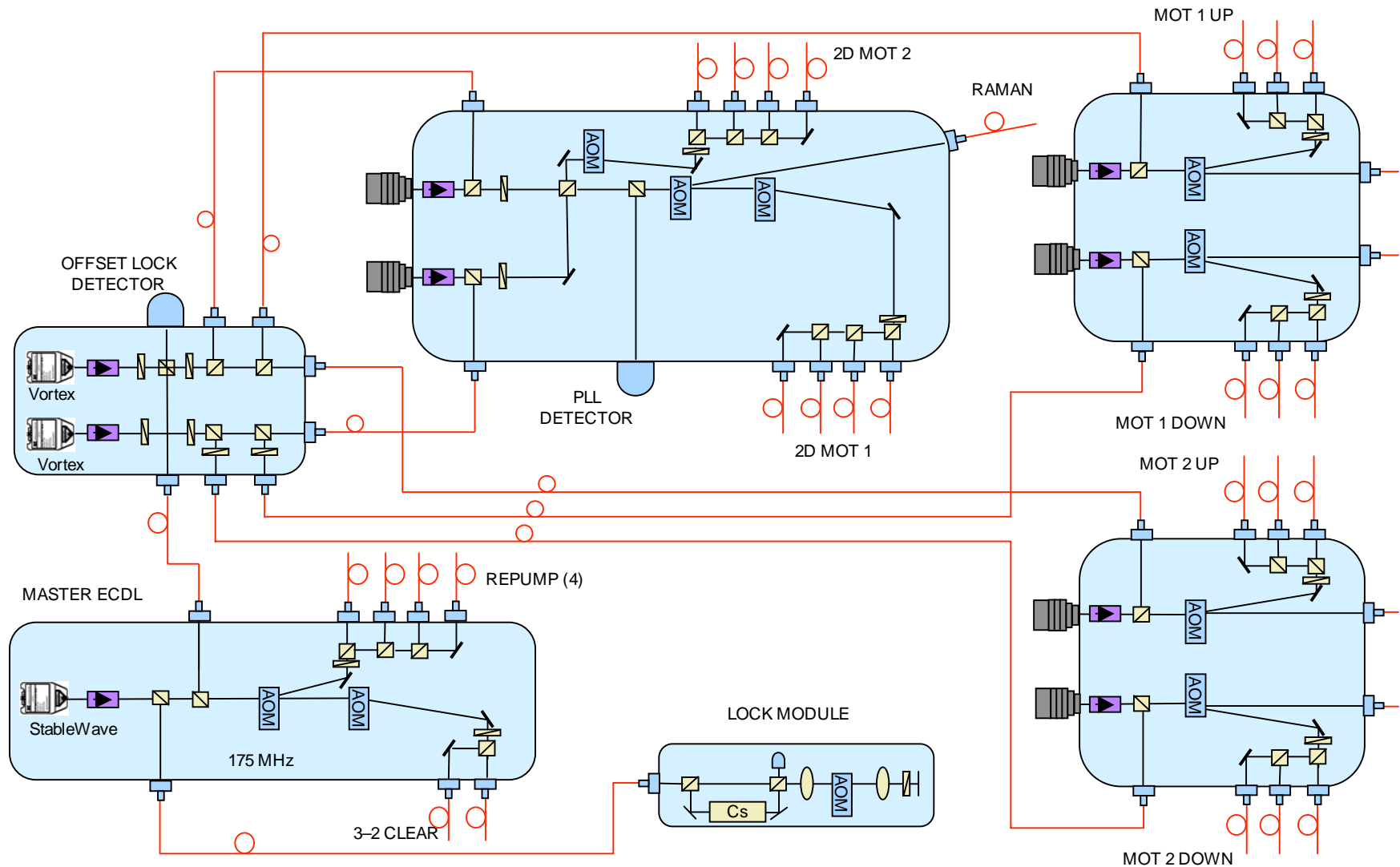


Left: Concept drawing of next-generation **mobile gradiometer**. The dual atom interferometers are shown in the cutaway section on the far left. The modular **laser and optics system** is contained in the instrument rack to the right.

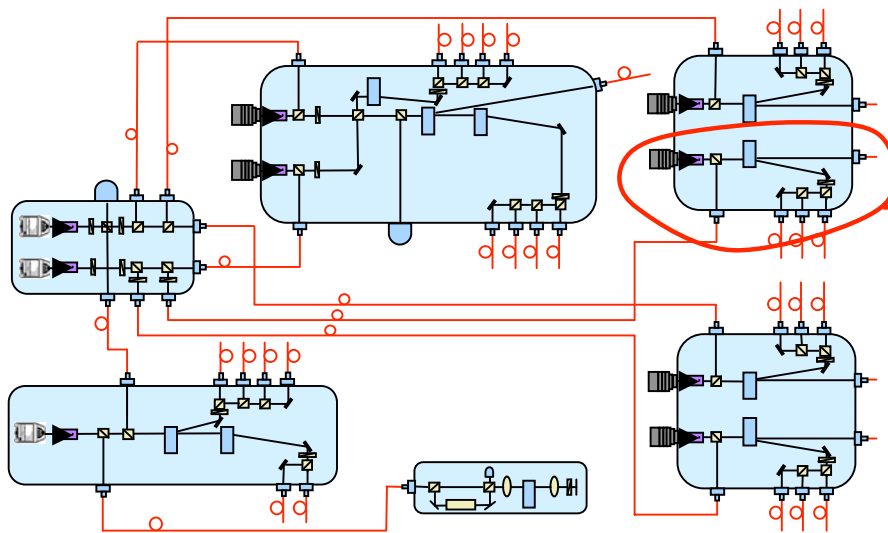
Above: Illustration of the next-generation **atomic physics package (APP)**. The atom fountain in this APP is based on a [1,1,0] launch geometry in a glass cell.



Mark II Laser and Optical System

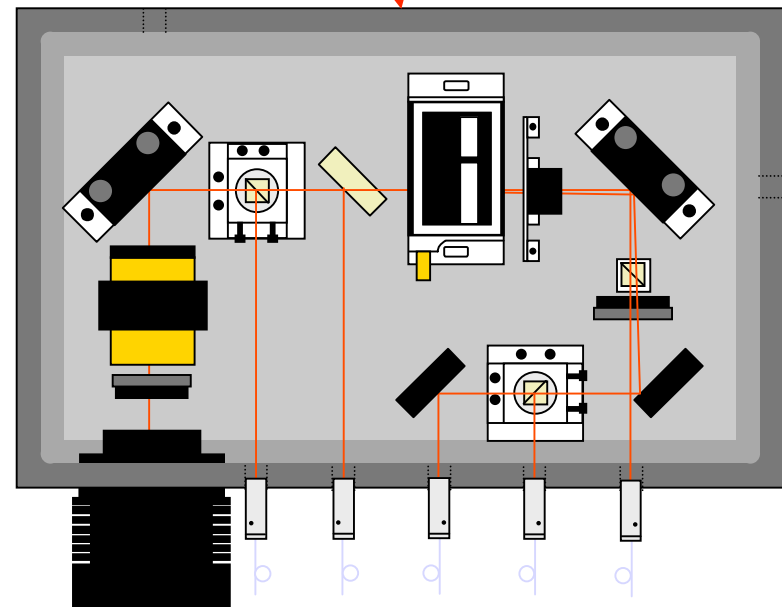


Compact Laser Amplifier Module



Individual modules will be engineered for thermal and mechanical stability.

Right: Illustration of single laser amplifier module



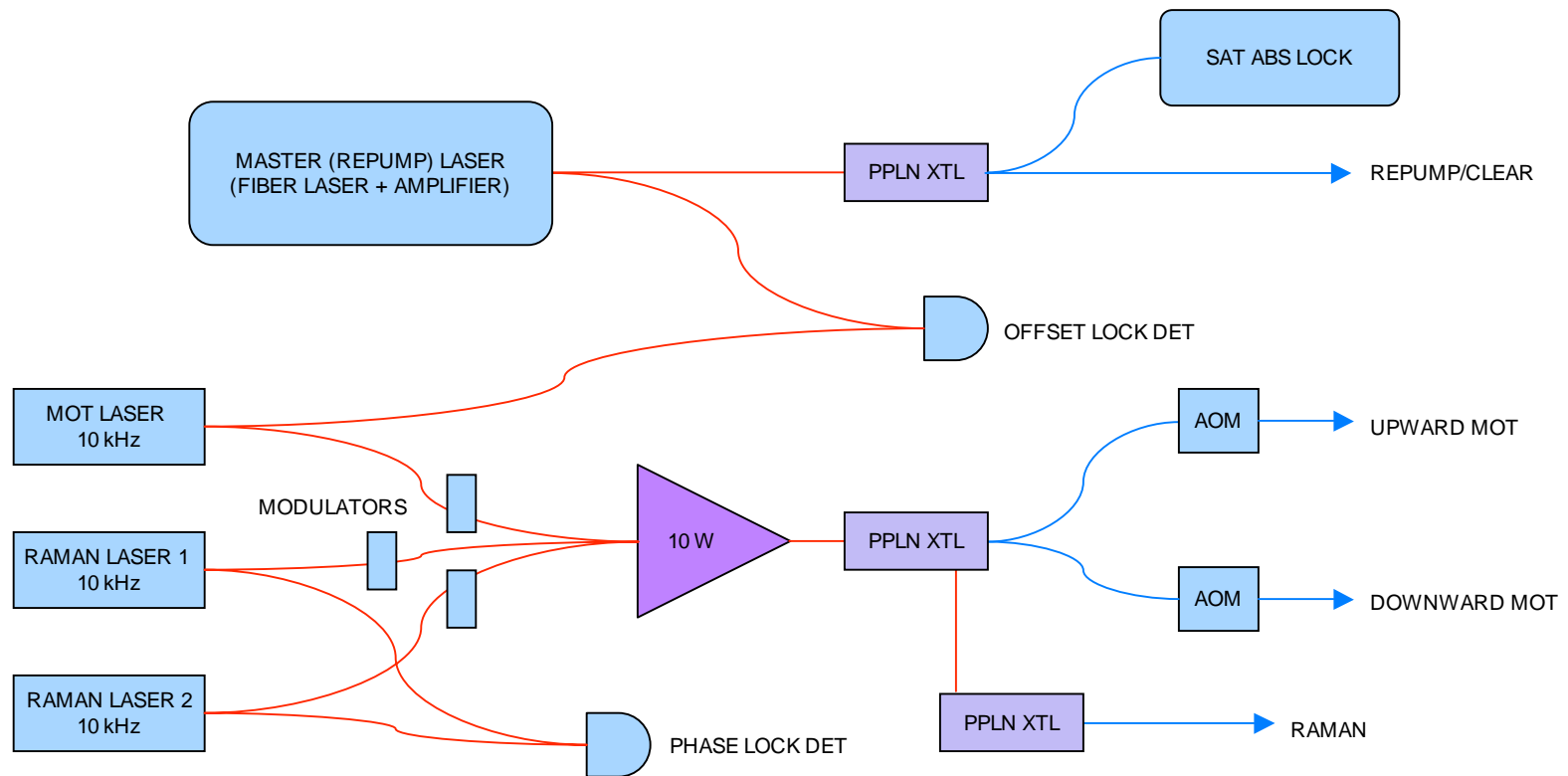
Technology Development: Fiber Laser System

- Fiber lasers offer extremely narrow linewidth (< 1 kHz), high power, and excellent beam quality along with telecom-standard ruggedness and reliability.
- With the use of nonlinear optical components, we can produce wavelengths throughout much of the visible and near IR spectrum.
- These lasers have wide applicability for earth science, both ground- and space-based.



Above: A commercial high-power, narrow linewidth distributed feedback (DFB) fiber laser module in a compact and rugged package for OEM integration.

Technology Development: Fiber Laser System



Conclusions and Future Goals

We have demonstrated a sensitive atom interferometer-based gravity gradiometer in the laboratory as the first phase of this instrument development effort, funded in part by the Advanced Component Technologies (ACT) program of NASA's Earth Science Technology Office. We are continuing development under the Earth Science Technology Office's Instrument Incubator Program (IIP), with the goal of producing a high-sensitivity mobile instrument.

Phase II design goals include:

- Compact and robust instrument for measurement on mobile platforms
- Improved environmental control, including magnetic fields, vibration and rotations.
- State-of-the-art atom interferometer performance
 - High fringe contrast
 - Atom shot-noise limited SNR
- State-of-the-art gravity gradient sensitivity
- Technology infusion for a future space instrument
- Analysis of long-baseline measurement issues

